G002

# Characterisation of Anisotropic Resistivity from Marine CSEM Data

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## SUMMARY

We present a method for interpreting marine controlled source electromagnetic data taking into account the vertical resistivity anisotropy which is commonly observed in earth structures based on an inversion approach to simultaneously derive both horizontal and vertical components of resistivity.

## Introduction

In the last decade, marine controlled-source electromagnetic (CSEM) surveying has been emerging as an important exploration tool for mapping hydrocarbon reservoirs. The principle of this technique, originally developed in the late 1970s (Cox *et al.* , 1980) to study the deep ocean lithosphere, lies in the interaction of an impinging electromagnetic field with the local sub-earth resistivity, such that the deformation observed in the electric or magnetic field measurements can be interpreted to create a resistivity model of the sub-earth. The higher resistive nature of hydrocarbon formations makes it possible to detect local anomalies which can be mapped into easily interpretable resistivity information. The survey uses a horizontal electric dipole (HED) emitting at low frequency (typically 0.01-10Hz) towed at around 30 m above the seafloor. The transmitted multi-component electric signal is measured at receivers located on the seafloor. Ideally, multiple components and multiple frequencies of the field are necessary to perform a reliable interpretation.

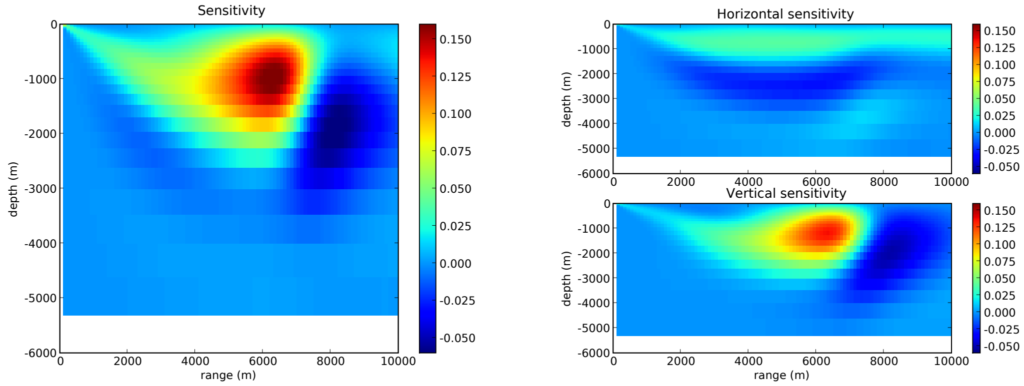
Interpreting the collected data is achieved via an inversion algorithm. The algorithm starts from an initial guess model and proceeds by minimising the discrepancy between a synthetic electromagnetic field calculated from the reconstructed resistivity model and the actual data measured at the receivers for a given frequency. Hence, the entire process of the inversion is conditioned by the choice of numerical model used to compute the synthetic electromagnetic field, and this model must be as close as possible to the physical reality of the sub-seafloor. For sake of simplicity, the models initially used to process CSEM data have assumed an isotropic earth electric resistivity, and sensible results have been obtained based on this assumption. However, it is known that the presence of electric anisotropy can yield significant variations in the electromagnetic field response measured at the seafloor, depending on the offset separating the source (the dipole) from the receiver, the geometry and the degree of anisotropy (Everett and Constable, 1999) (Tompkins *et al.* , 2004) (Lu and Xia, 2007). In such cases, incorporating electric anisotropy in the resistivity model will be beneficial to CSEM data interpretation. The first step in implementing sub-earth anisotropy is to consider "uniaxial" vertical anisotropy, where the electric resistivity of the rocks remains horizontally constant and the vertical resistivity differs from the horizontal one, which is the configuration likely to be encountered in the presence of fine-scale, interbedded geological strata (Everett and Constable, 1999). In this simple configuration, the electric anisotropy tensor reduces to a $3 \times 3$ diagonal matrix in which the first two values are the horizontal resistivity $\rho_h$ and the third one the vertical resistivity $\rho_v$. The degree of anisotropy can then be characterised by the ratio $\lambda^2 = \frac{\rho_v}{\rho_h}$.

The scope of this paper is to introduce a method for processing electric field data characterising horizontally isotropic media (i.e. vertical anisotropic media) via an inversion algorithm accounting for this particular type of anisotropy. The first part will be dedicated to analyse the sensitivity of the electric field with respect to variations of resistivity below the seafloor in some simple configurations, whereas in the second part, we will present inversion results.

## Anisotropic sensitivity

We define the anisotropic sensitivity as the variation of the electric field measured at the receiver with respect to a small variation of horizontal or vertical resistivity in a particular chunk of earth. Hence the values of sensitivity are strongly conditioned by the choice of discretisation, and for one-dimensional models, where the sub-earth is represented by horizontally infinite layers stacked vertically, they depend on the layer thickness. In order to counteract the decay of the sensitivity kernel with depth, we construct a model discretisation with 46 layers of regularly increasing thickness from the top of the discretisation domain to its bottom.

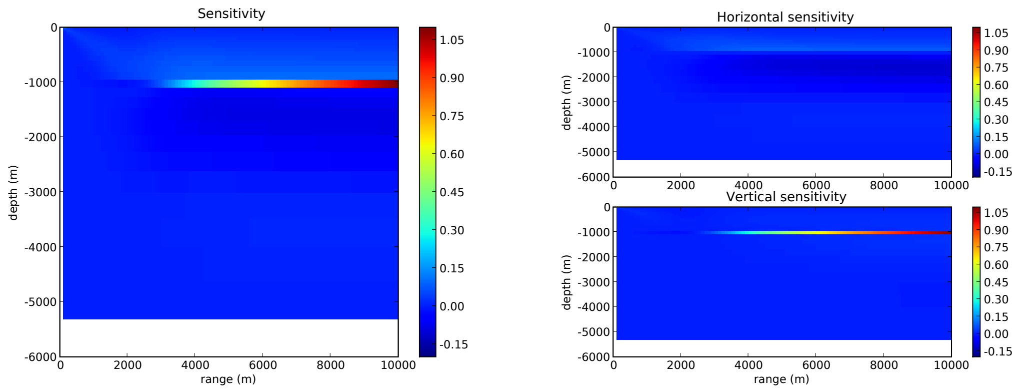
Figure 1 presents a comparison between the isotropic and the anisotropic log-sensitivity of the electric field measured at 0.2 Hz along a 10 km line of 100 receivers with respect to an 1 $\Omega$.m isotropic half-space below a 1000 m seawater column of resistivity 0.313 $\Omega$.m in the inline configuration (i.e. the receivers are aligned with the dipole orientation line); and in Figure 2 a similar comparison when a 50 $\Omega$.m isotropic target of 131 m thickness is embedded 820 m below the seafloor in a similar background. The log-sensitivity is expressed by $\frac{\partial \log_{10} E}{\partial \log_{10} \rho}$, where $E$ is the amplitude of the electric field measured at the receiver, and is dimensionless.




(a) Isotropic (b) Anisotropic

Figure 1: Sensitivity of an isotropic 1 $\Omega$.m half-space at 0.2 Hz in the inline configuration.

The sensitivity pattern in Figure 1(b) confirms the known fact that in the inline configuration the variations of radial electric field are mostly affected by vertical resistivity, which dominates the interaction of the TM mode with the conductive medium. The decay of sensitivity to vertical resistivity at offsets larger than 7 km is due to the reflection of the electromagnetic field at the sea/air interface and is confirmed by the fact that the sensitivity to horizontal resistivity becomes constant at these ranges.




(a) Isotropic (b) Anisotropic

Figure 2: Sensitivity of an isotropic 50 $\Omega$.m target embedded in an isotropic 1 $\Omega$.m half-space below the seafloor at 0.2 Hz in the inline configuration.

When a highly resistive target is embedded in a similarly featured background, the electric field becomes mostly sensitive to the target, since sensitivity increases where the resistivity is high. In a similar fashion as for the half space, the radial electric field is mostly sensitive to variations of the vertical resistivity in the target. However, in contrast to the halfspace case, sensitivity to horizontal resistivity in the overburden is greater than to vertical resistivity. Studies prove that a similar conclusion can be drawn for the broadside configuration (when the receivers line is perpendicular to the dipole).

**Inversion**

The inversion algorithm is an adaptation of the one presented by Constable *et al.* (1987). The algorithm minimises the misfit between the modelled data and the input data, the latter being associated with an error bar which weights it in the objective functional. When inverting synthetic data, synthetic noise equal to 2.5 % of the amplitude is added to the data, as well as a noise floor equal to $10^{-16}$ V.A$^{-1}$.m$^{-2}$. The minimal RMS misfit value (i.e. tolerance) required to be reached by the inversion is computed as the RMS misfit between the noisy and non noisy data.

The first inversion example is done on amplitude and phase synthetic data characterising an anisotropic half-space of 1 $\Omega$.m horizontal resistivity and 2 $\Omega$.m vertical resistivity, below a 1000 m seawater column of resistivity 0.313 $\Omega$.m. Like for the sensitivity analysis inline data is collected along a 10 km line, and data with amplitude values below the noise floor are trimmed off. The initial model is set to an 1 $\Omega$.m isotropic half-space, which provides a RMS misfit equal to 85.5202. Figure 3 presents the reconstructed model obtained after 5 iterations, when the RMS has reached the required tolerance of 0.65, which model matches almost perfectly the true one. Figure 4 respectively presents the amplitude strength and misfit, and the phase strength and misfit at the same positions, at every receiver position on the line.

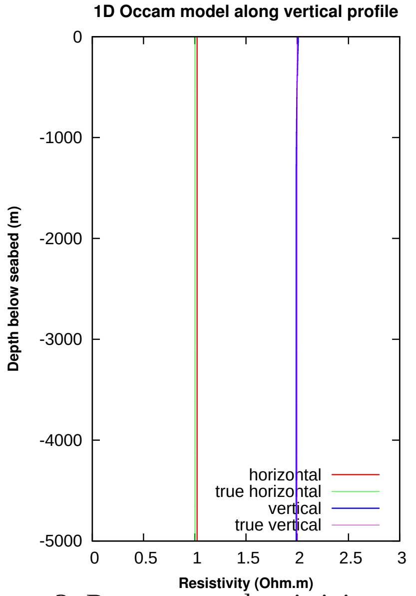



Figure 3: Reconstructed resistivity model.

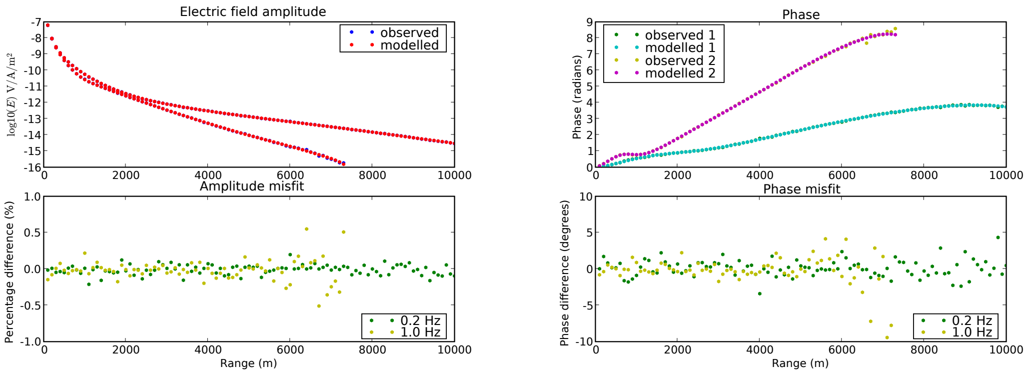



Figure 4: Field strength and misfit.

The second example is the case of an 50 $\Omega$.m target of thickness 50 m, buried 1000 m below the seafloor. The model is initialised with an uniform 1 $\Omega$.m isotropic half-space, which gives a misfit equal to 124.0242, and after 49 iterations the model in Figure 5 is recovered, for which the RMS misfit has been lowered to 0.7. The amplitude response and amplitude misfit, as well as the phase response and the phase misfit, are respectively displayed in Figure 6. As expected considering the sensitivity analysis (little sensitivity to the horizontal resistivity of the target), the vertical resistivity of the target is well recovered, whereas its horizontal resistivity is not. Both vertical and horizontal resistivities of the background are more or less well recovered, the better results being at shallower depths. For larger depths the vertical resistivity of the target creates a screen effect which hides the vertical resistivity of the background for large depths. The isotropic inversion of a similar dataset would produce a model where the resistivy profile would contain greater oscillations in the overburden and where the target would be too shallow (Tompkins *et al.* , 2004).

## Conclusion

These two simple examples prove the robustness of the algorithm with regards the higher complexity of the inverse problem in anisotropic media. The efficiency of the method does not depend of the anisotropy ratio which characterises the different areas of the sub-seafloor, but on the sensitivity to the electric resistivity characterising these areas. In the presence of a thin resistive horizontal layer, the senstivity kernel is mostly dominated by the vertical resistivity of the target, which implies a better recoverability of the vertical resistivity of the target than its horizontal resistivity. Tests on survey results confirm that, using appropriate data, significant electric anisotropy in the earth can be detected and quantified.

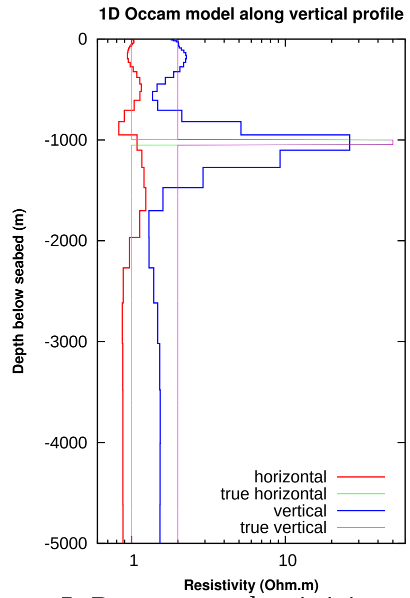


Figure 5: Reconstructed resistivity model.

Higher dimensional problems, such as 2D or 3D, will need to be tested, in order to account for for the horizontal variability of the earth, which is likely to be encountered with real field data.

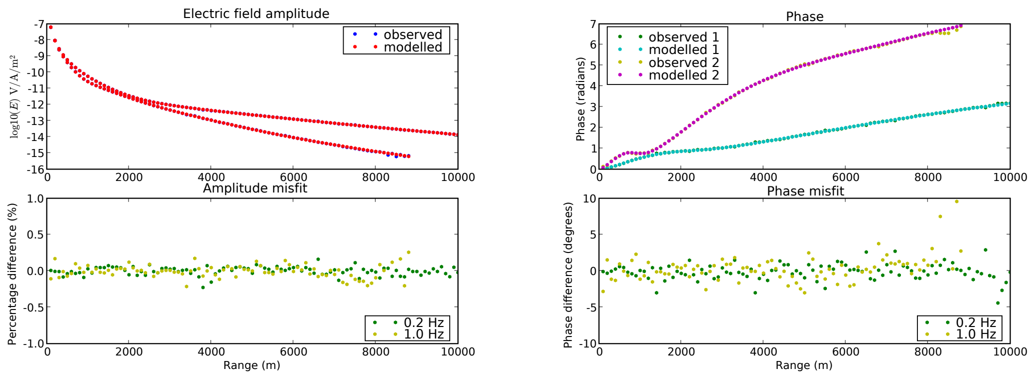


Figure 6: Field strength and misfit.

## References

Constable, S.C., Parker, R.L., and Constable, C.G. [1987] Occam's inversion: a practical algorithm for generating smooth models from electromagnetic sounding data. *Geophysics* 52(3), 289–300.

Cox, C.S., Filloux, J.H., Gough, D.I., Larson, J.C., Poehls, K.A., Von Herzen, R.P., and Winter, R. [1980] Atlantic lithosphere sounding. *J. of Geomagnetism and Geoelectricity* 32(Suppl. I), SI 13–SI 32.

Everett, M.E., and Constable, S.C. [1999] Electric dipole fields over an anisotropic seafloor: theory and application to the structure of 40 Ma Pacific Ocean lithosphere. *Geophys. J. Int.* 136, 41–56.

Lu, X., and Xia, C. 2007. Understanding anisotropy in marine CSEM data. *In: 77th SEG Annual Meeting, San Antonio*.

Tompkins, M.J., Weaver, R., and MacGregor, L.M. 2004. Effects of vertical anisotropy on marine active source electromagnetic data and inversions. *In: 66th EAGE Conference and Exhibition, Paris*.